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ABSTRACT

Inertial confinement fusion (ICF) target designs are considered which may have very high gains ($\sim$ 1000) and low power requirements (< 100 TW) for input energies of $\sim$ one megajoule. These include targets having very low density shells, ultra thin shells, central ignitors, magnetic insulation, and non-ablative acceleration.

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The earliest ICF target designs were solid and hollow spheres of DT fuel.[1] Solid spherical targets have minimum fabrication cost. Given high performance lasers (with respect to wavelength, efficiency, power, rep rate, and pulse shaping) these targets produce minimum yield fusion microexplosions with high enough gains for practical applications, have near minimum laser energy requirements, and make possible minimum size power plants (~ a few hundred MWe). An important disadvantage of solid targets is the very high power requirement, since the cost of all ICF drivers increases with power.

Use of hollow rather than solid targets reduces the required driver power from more than 1000 TW to ~ 100 TW. In order to relax the driver wavelength (or voltage) and efficiency requirements, the mass of the fuel in the canonical target has been increased. Also some intermediate and high Z coatings have been introduced for ablators, shields, and pushers. The larger fuel mass has increased the required driver energy (to ~1 MJ) but has relaxed the target fabrication cost limitations (to 10-100 cents/pellet).

For some ICF driver technologies, improved target designs would be advantageous to further reduce the power and efficiency requirements. Increasing the target gain also increases the yield which would allow further increase in the target fabrication cost. We consider several target designs which may be capable of achieving high performance levels.

THEORETICAL POSSIBILITY OF HIGH PERFORMANCE WITH VERY LOW DENSITY TARGETS

Consider a target which is made entirely of very low density materials (0.2 g/cm^3) and is moderately hollow ($\frac{\Delta R}{R} \simeq 0.1$). Figure 1.

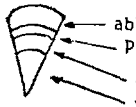

Figure 1 - Sections of a hollow spherical inertial fusion target made of low density materials.

Gain 1000 will be achieved if the following conditions are satisfied

- burn efficiency 40%, 1.4×10^{11} J/g
- implosion velocity 2×10^7 cm/s, 2×10^7 J/g
- *implosion efficiency* 14%
- mass of DT 10^{-3} g

The compressed spherical ρr and the DT burn efficiency ϕ are related by[2]

$$\frac{\phi}{1 - \phi} = \frac{r\rho}{6}$$

Then $r\rho \simeq 4.5$ g/cm^2 for $\phi = 0.4$. For $r\rho = 4.5$ and $M = 10^{-3}$g, the density is

$$\rho^2 = \frac{\frac{4\pi}{3}(r\rho)^3}{M}, \quad \rho = 600 \text{ g/cm}^3$$

An implosion velocity of 2×10^7 cm/s, corresponding to a specific energy of 2×10^7 J/g, generates maximum density when the DT electrons are degenerate. Then

$$\varepsilon = \frac{3}{5}\,\varepsilon_{Fermi} = 3 \times 10^5\,\rho^{\frac{2}{3}}\ \mathrm{J/g}$$

$$\text{or } \rho \approx 600\ \mathrm{g/cm^3} \text{ when } \varepsilon = 2 \times 10^7\ \mathrm{J/g}$$

The electron degeneracy condition is

$$\frac{5\pi^2}{12}\left(\frac{\theta}{\varepsilon_{Fermi}}\right)^2 << 1$$

or the electron temperature $\theta \leq 100$ eV for $\rho \approx 600\ \mathrm{g/cm^2}$. This may be achieved by pulse shaping.[1] In order to ignite an all DT pellet a central core having $\rho r \approx \frac{1}{2}\ \mathrm{g/cm^2}$ must be driven to ≈ 10 Kev temperature.[2] The mass corresponding to $0.5\ \mathrm{g/cm^2}$ is $\sim 10^{-3}$ of the total whereas the specific energy at 10 Kev is $\sim 10^{2}$ of the average, so that the ignition energy is small compared to the energy of compression.

The implosion efficiency may be roughly estimated as follows. Assume the ablator weighs ≈ 4 mg and has density $0.2\ \mathrm{g/cm^3}$. Then if the 5 mg of DT and ablator is initially a spherical shell with $\frac{\Delta R}{R} \sim \frac{1}{10}$, the initial radius is ≈ 3 mm. Taking an average radius of 2 mm, corresponding to a volume of $\frac{1}{30}\ \mathrm{cm^3}$, an average driving pressure of $\simeq 5$ Mb is required

to accelerate 1 mg to 2×10^7 cm/sec. If the peak pressure is 10 Mb, then for a 1 μm laser the peak power is ≈ 10-20 TW and the intensity is ≈ 50 TW/cm^2.[2,3] Using the flux limit equation, an electron temperature of 400 ev follows, corresponding to a velocity of 2.5×10^7 cm/sec. The peak implosion efficiency is[2]

$$\text{Implosion Efficiency} \simeq \frac{V_{impl}}{V_{impl} + K\,V_{exh}} \simeq \frac{0.2}{.2 + 3 \times .25} \simeq 0.2 \text{ peak}$$

where $V_{exhaust}$ is the velocity of the ablated material, V_{impl} the velocity of imploded material, K corrects for the heating of the previously ablated material, and classical electron transport is assumed. At lower implosion velocities, the efficiency is smaller. LASNEX calculations with 1 μm light show an average efficiency of somewhat less than 10%. This efficiency may be increased by use of shorter wavelength laser light.[2]

$$P \sim I^{\frac{2}{3}} \rho_c^{\frac{1}{3}}$$

$$V_{exh} \sim \left(\frac{I}{\rho_c}\right)^{\frac{2}{3}}$$

At constant ablation pressure,

$$V_{exh} \sim \frac{1}{\rho_c} \sim \lambda^2$$

where P is the ablation pressure, ρ_c the critical density corresponding to laser wavelength λ, and I the laser intensity. Hence by reducing

the wavelength, the exhaust velocity at constant ablation pressure may be reduced sufficiently so that the implosion efficiency can be increased to 15%.

In order to realize high performance levels in practical implosions, a number of important constraints must be observed, involving symmetry, stability, entropy, absorption, fabrication, etc.

The implosion must be sufficiently spherically symmetric. In the example above, the central $\frac{1}{2}$ g/cm^2 must be sufficiently spherical to efficiently ignite. Since the density is 600 g/cm^3, the compressed radius is $\approx 10^{-3}$ compared to an initial radius of 0.3 cm - a convergence ratio of 300. This implies implosion accuracies better than 1%, [from $\Delta r \sim \Delta(Vt)$]. By use of multiple beams, electron transport in a low density atmosphere, and shimming, it is theoretically possible to achieve such high convergence ratios.[2]

Shimming refers to the correction of implosion asymmetries by introducing non-spherical variations in the shell radius and thickness during fabrication. In order to fully exploit shimming it is necessary to have sufficiently accurate two dimensional implosion codes, diagnostic methods capable of experimentally resolving asymmetries (e.g. radiochemical techniques), and highly reproducible drivers.

Fluid instabilities. A very low density target shell may have a moderate aspect ratio ($\sim \frac{1}{10}$). Consequently the growth of fluid instabilities may be sufficiently controlled by means of density gradients in the

ablation region having scale heights comparable to the wavelength of the most damaging perturbations. These scale height gradients may be controlled if necessary by introducing an energy spread in the electrons or ions which drive the ablation.[4]

Entropy is controlled by pulse shaping and by avoiding excessive preheat. Experiments which have been carried out at LLL and KMSF show that the modest pulse shaping requirement of moderately hollow targets can be achieved. The preheat may be adequately controlled by shielding - seeding some high Z material in the ablator material adjacent to the DT; and by enhancing inverse bremsstrahlund absorption (and reducing non-collisional absorption) vis use of intermediate Z ablators, short wavelength lasers, and lower intensities.[2]

Efficient absorption is obviously essential to high performance. Plasma instabilities and resonance phenomena do not absorb laser light efficiently.[5] Efficient absorption may be achieved via inverse bremsstrahlung at relatively low intensities ($< 10^{14}$ w/cm^2) in material with $Z \approx 5$-10 (higher Z materials may have excessive energy losses by X-rays) with light that has a relatively favorable incidence angle and a short wavelength.

$$\text{absorption length} \sim (\rho^{-2} Z^{-1} \theta^{3/2} \lambda^{-2}) \sim \lambda^{2} Z^{-1} \theta^{3/2}$$

Fabrication poses special problems for targets which are made entirely of very low density materials. Except for low density foams

which are not sufficiently homogeneous, all of these low density materials are cryogenic when in the liquid or solid state. It is in principle possible to make hollow shells of frozen DT and then coat these shells with mixtures of hydrogen and noble materials such as neon and argon. Alternatively, a solid sphere of liquid DT may be appropriately coated and then used to make a hollow gaseous target in situ.[6,7] A spherically convergent laser pulse would be used to suddenly melt or vaporize the pellet while strongly vaporizing a small region in the center. Expansion of this gaseous core would then generate the hollow sphere. Another alternative would be to use either a spherical or parallel beam of laser light, ions, electrons, etc., to volume heat and vaporize an ultra thin target, which upon expansion would be transformed into a low density target. This approach has the advantage that one or more shells in the ultra thin target need not be cryogenic during normal fabrication. An advantage of in situ fabrication is that during expansion into vacuum, small fabrication imperfections would be healed. In order to avoid collapsing back to higher densities when the implosin pressure is applied, a preheat temperature of a few eV is required.

Although the above analysis indicates gains of 1000 should be achievable with 100/KJ/20 TW short wavelength lasers imploding moderate

aspect ratio low density shells, detailed LASNEX calculations show much smaller gains. Typically the compressional energy is several fold higher than the theoretical minimum in order to achieve efficient ignition. For hollow shell implosions there is a conflict between the entropy and ignition conditions: The pulse shape cannot achieve small entropy changes ($\theta \ll \varepsilon_{Fermi}$) while not allowing the inner edge of the shell to run away from the outer edge, and at the same time causing the central core to reach ignition conditions ($\theta \gg \varepsilon_{Fermi}$). As the laser energy is increased to 1 MJ and larger, the theoretical gain of 1000 may be approached because the inertial burn time increases with DT mass so that the entropy and ignition requirements are relaxed.

VERY THIN SHELL TARGETS

It has been proposed[8] that high performance levels may be achieved with targets having very high aspect ratio ($\frac{1}{100}$) shells of moderate-high density materials (2-20 g/cm^3), and that stable acceleration of such shells is feasible. Note that if 2 g/cm^3 materials are used the shell has the same mass at the same radius, but is $\frac{1}{10}$ as thick at 10 times the density, as in the low density approach described above. As far as the required power is concerned the thinner, higher density shell has no significant advantage over the corresponding low density shell

$$\bar{P}R^3 \sim \rho R^2 \Delta R \dot{v}^2, \; m \sim \rho R^2 \Delta R$$

and

$$\text{power} \sim \bar{P}R^2 vf \sim (m\rho\Delta R)^{\frac{1}{2}} v^3 f$$

where $\bar{P}$ is the average implosion pressure, v the implosion velocity, m the target mass, and f the implosion efficiency. The key parameter is $\rho\Delta R$, so that to a first approximation a low density moderate thickness shell has the same power requirement as a moderate density ultra thin shell of the same $\rho\Delta R$ and m. Similarly the potential gain of the low density shell is approximately the same as that of the higher density shell, providing some care is used in the initial stages of the pulse shape applied to the low density shell. However the thin shell is drastically less stable

$$A = A_0 \exp \int \sqrt{\frac{2\pi}{\lambda} a} \;\; dt$$

where A is the amplitude, λ the wavelength, and a the acceleration. Since the worst λ is $\sim \Delta R$, and $at^2 \sim R$ for const. v, we have

$$A \sim A_0 \exp \sqrt{\frac{R}{\Delta R}}$$

so that the thin shell has $\sqrt{10}$ more e foldings of instability growth. Consequently much longer wavelengths grow to disastrous amplitudes than for the lower density shell. These wavelengths are so large that it is no longer possible to control their growth by density gradients because the gradient scale height must be comparable to the wavelength and not enough material is in the shell to generate such scale heights. LASNEX calculations show disastrous failure during acceleration.[9]

It has been asserted that these ultra thin shells may be stabilized by other means, e.g. because the acceleration is so slow,[10] or by turbulence,[11] or by resonant acceleration.[12,12a] The slow acceleration conjecture is contradicted by LASNEX calculations. Turbulence stabilizes by density gradient formation which is insufficient. Resonant acceleration depends on the presence of some other damping mechanism, in this case density gradients, to control the growth of the modes whose growth rate is increased by the resonant driving. However again density gradients are ineffective.

Overall these ultra thin shells have no significant advantage in gain or power and a probable fatal instability difficulty, with a minor advantage in pulse shaping.† Re fabrication, at least some non-cryogenic shells may be used (not including the DT fuel) but an ultra smooth surface finish is required. If several alternate cryogenic/non-cryogenic layers are required in order to achieve central ignition, the fabrication problem appears to be exremely difficult.

†LASNEX calculations show much smaller gains than claimed by Afans'ev et al.[14]

There is however one possible means of controlling the growth of fluid instabilities in ultra thin shells which merits detailed calculation. Since the driving pressure is of order a few megabars, if heating by electrons, X-rays, thermal waves, and shocks is kept sufficiently small, then sufficient stabilization may be achieved by the shear strength of the shell - particularly when dynamic effects and the increase in shear strength and melting point with pressure are included. Calculations with 2D elastic-plastic-hydrodynamic computer programs in which the stress is represented as a tensor and realistic stress-strain failure criteria are used predict substantial damping of fluid instabilities when the shear strength is of order 1% of the driving pressure.[13] However if the shell is made too thin, then the growth of relatively long wavelength perturbations is not effectively controlled by material strength.

TARGETS WITH CENTRAL IGNITOR

The performance of hollow targets may be increased somewhat by use of a small central ignitor.[†14] The required implosion velocity of the outer shell may then be reduced from 2×10^7 cm/s to $\sim 1.4 \times 10^7$ cm/s. Twice as much fuel may then be imploded for the same energy to about one third the density (200 g/cm^3). For the low density case considered above, the ρr would change by $(M\rho^2)^{1/3}$ or $(2 \times \frac{1}{9})^{1/3} \approx 0.6$, from 4.5 g/cm^2 to 2.7 g/cm^2. This would change the burn efficiency from $\frac{4.5}{10.6} = .43$ to $\frac{2.7}{8.7} = .31$. Hence the yield would increase by $2 \times \frac{.31}{.43} = 1.45$.

† Conceptually this design is intermediate between solid and hollow designs.

A cross section of a hollow shell with central ignitor is shown in Figure 2.

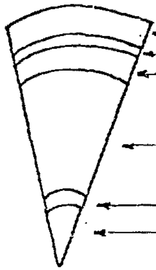

Figure 2 - Sector of a spherical inertial fusion target having a central ignitor and an outer fuel layer. This target is capable of very high gain and requires low driving powers.

During convergence the inner part of the outer shell would reach velocities greater than 1.4×10^7 cm/sec. Upon collision with the relatively light weight inner pusher, additional velocity multiplication to $> 2 \times 10^7$ cm/s occurs. This is sufficient to compress and ignite the inner fuel. The inner fuel then produces sufficient energy to ignite the outer fuel through the intervening pusher (which if necessary could be fissionable by DT neutrons). A potential advantage of this approach is the gas region is heated to several hundred ev, and electron conduction in this region may improve the symmetry of the ignitor implosion. Two difficulties

are: mixing of the ignitor pusher material into the outer fuel, which might make ignition of the outer fuel difficult or impossible; and fabrication. It is not clear that this target can be fabricated without introducing such large perturbations at the seams (when the ignitor is inserted through the outer shell) so that the yield is degraded somewhat. Finally the outer surface of the ignitor pusher is driven purely hydrodynamically, and must either be made very thick compared to the radius ($\sim \frac{1}{3}$) or have a surface finish of 10's - 100's of Å, and possible both.

Non-central ignitors are also possible. The simplest is low density gas inside a hollow shell; or multiple layers may be used in the outer shell. So far these do not perform as well in LASNEX calculations as the central ignition design. There are a number of va iations of the central ignitor, e.g., the central fuel may itself be moderately hollow, and the ignitor pusher may be relatively massive and high density, light and low density, etc. The optimum ignitor has not yet been determined.

TARGETS WITH MAGNETIC INSULATION

The implosion velocity required to reach thermonuclear temperatures may also be reduced if the ignited region contains a magnetic field to reduce cooling by electron conduction, and if the density is sufficiently low so that cooling by bremsstrahlung is not dominant.[15] However with drivers capable of generating high energy densities use of magnetic insulation does not lead to significant increases in gains or reductions

in p[illegible]r because reducing the implosion velocity reduces the DT density and burn efficiency (as in the ignitor example). In addition the critical size and ignition velocity of the DT is limited by ion conduction as well as by what size initial magnetic field it is practical to generate. Finally in order for a minimum mass of low density DT to ignite an adjacent larger mass region of high density DT, the density mismatch must not be too large ($\gtrsim 10$). Otherwise a strong enough front is not propagated into the dense DT to achieve ignition.

NON-ABLATIVE ACCELERATION

The two principal inefficiencies in the ICF fusion process are in the ablative implosion and in the driver: the former is of order 10% efficient and the latter may be substantially less than 10% efficient. We consider the following ideal - apparently impractical - scheme in which the input energy to the target is reduced from 1 MJ to 100 KJ, the input energy to the driver reduced from more than 10 MJ to of order 100 KJ, and the driver power reduced from ~ 100 TW to ~ 1 GW. (With the resulting gains ~1000, the driver energy and pellet mass could of course be reduced by one or more orders of magnitude to make smaller reactors, or to make GWe size reactors with higher driver rep rates.) Imagine the spherical surface of a hollow DT shell divided into sectors, e.g. 12 pentagonal sectors. Each of these sectors is to be accelerated magnetically or electrostatically with high efficiency in 12 "guns" to velocities of 2×10^7 cm/s.† If the acceleration and aiming could be sufficiently precise, the twelve sectors could be assembled to form a sufficiently perfect spherical shell moving inward at 2×10^7 cm/sec.

†The required acceleration length is >> 100 meters.

A less efficient and less demanding scheme technologically is to electrostatically or magnetically accelerate $10\text{-}10^4$ small pellets to velocities of 2×10^7 cm/s over a distance of about one kilometer. These pellets are directed spherically symmetrically onto a target where they are vaporized by impact with a thin outer shell and penetrate into a region of gas which is heated to temperatures of ≈ 100 ev generating pressures of ≈ 10 Mb. Electron conduction strongly smooths the irregularities due to the finite number of pellets. This pressure implodes a double shell target with a thick low density outer shell. Figure 3.

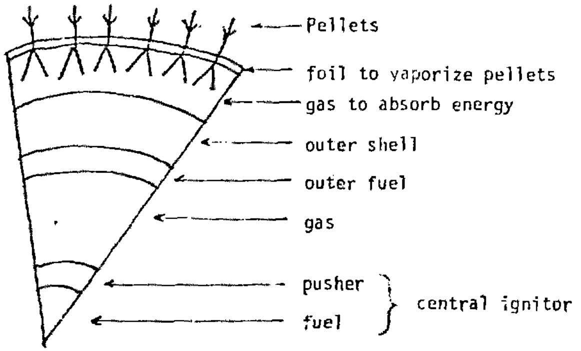

Figure 3 - Sector of a spherical inertial fusion target driver by many hypervelocity micropellets. Outer shell vaporizes pellets and smooths driving pressure. Inner target is a central ignitor design.

The practicality of this approach depends on the technical details of the pellet accelerating system which are not yet fully analyzed, Under some conditions it may be advantageous to accelerate the multiple pellets

ablatively with lasers. Calculations[16] show that medium to short wavelength lasers operating in a relatively high efficiency $> 100\ \mu s$ mode can accelerate pellets to 2×10^7 cm/s in distances of ~ 100 m with an ablative efficiency of ~ 10-20%. Unfortunately, for CO_2 lasers the ablation efficiency is only a few percent. Most important, the laser power is reduced more than 1000 fold from ~ 100TW to $\lesssim 10$-100 GW.

SUMMARY

Very low density target designs appear to be capable of approaching gain 1000 with appropriate 1 MJ/100 TW drivers. These performance levels may then be achieved or exceeded by adding a central ignitor. The central ignitor target appears to be well suited to implosion by lasers, ions, and electron beams; and possibly also by a large number of tiny pellets accelerated by magnetic or electrostatic means, or by ablation with 100 GW lasers.

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